Proc. NIPR Symp. Upper Atmos. Phys., 4, 9–19, 1991

WHISTLER-TRIGGERED VLF EMISSIONS IN THE ELECTRON SLOT AND INNER RADIATION BELT, AS OBSERVED AT MOSHIRI (L=1.6)

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Abstract: The morphological characteristics of whistler-triggered VLF emissions including diurnal, seasonal variations, K_p dependence, latitudinal distribution and spectral shape, have been investigated based on the VLF data obtained at Moshiri (L=1.6) in Japan during a ten year span (1976 to 1985). The following results have emerged; (1) There does not seem to exist a clear tendency of whistler-triggered emissions to occur at a particular local time, (2) equinoctial maximum in occurrence probability is recognized, (3) the occurrence probability seems to increase with K_p index, (4) the occurrence L shell is localized in two regions; one is L=2.1 to 3.4 (the electron slot region) and the other is just around L=1.6 (the inner radiation belt), and (5) a whistler-triggered emission is characterized by an initial quasi-constant frequency component and a subsequent drastic frequency drift mainly with df/dt= 10–20 kHz/s. These characteristics are satisfactorily interpreted in terms of the gyroresonance interaction between lightning-generated whistlers and energetic electrons, with a reference to the previous results of lightning-induced particle precipitation.

1. Introduction

The gyroresonance interaction between whistler-mode waves and energetic electrons is an important process in the magnetosphere. Its consequences are the linear wave amplification and generation of new VLF emissions, and also the wave-induced pitch angle scattering of magnetospheric particles and the associated particle precipitation into the lower ionosphere (*e.g.*, BRICE, 1964).

Lightning-generated whistlers are recently found to induce the particle precipitation (HELLIWELL *et al.*, 1973; CARPENTER and LABELLE, 1982; LEYSER *et al.*, 1984; VOSS *et al.*, 1984; INAN *et al.*, 1985; INAN and CARPENTER, 1987; CARPENTER and INAN, 1987), but much remains to be learned about the contributions to the loss of radiation belt electrons of magnetospheric waves of different origins such as hiss, chorus, whistlers, VLF transmitter signals *etc*. So, in order to investigate the role of lightning-generated whistlers in the magnetospheric wave-particle interaction process and in the removal of energetic electrons from the radiation belts, we have studied the general characteristics of VLF emissions which are triggered by lightning-generated whistlers as a consequence of strong nonlinear gyroresonance interaction. The presence of such whistler-triggered VLF emissions has long been known from the beginning of whistler studies (HELLIWELL, 1965), but no reports have been published on the statis-

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tical features of those whistler-triggered VLF emissions based on the ground-based VLF data. Hence, the present paper will be the first attempt to examine the statistical characteristics of whistler-triggered VLF emissions including diurnal, seasonal variations, K_p dependence, latitudinal distribution and spectral shape on the basis of VLF data observed at Moshiri ($L=1.6$) in Japan during a ten year span from 1976 to 1985. Lightning-induced particle precipitation as the particle-side aspect of the gyroresonance interaction has been investigated currently by many authors (HELLIWELL *et al.*, 1973; CARPENTER and LABELLE, 1982; LEYSER *et al.*, 1984; VOSS *et al.*, 1984; INAN *et al.*, 1985, 1988; INAN and CARPENTER, 1987; CARPENTER and INAN, 1987). So, with a reference to these previous results of lightning-induced particle precipitation, we have discussed on the general characteristic of whistler-triggered emissions with the idea of gyroresonance interaction.

2. VLF Data Base

The present study is based on the VLF observations made at Moshiri (Inv. lat. 38°N; $L=1.6$) in Japan (HAYAKAWA *et al.*, 1975, 1985; HAYAKAWA, 1989) during ten years from 1976 to 1985. VLF wideband signals (up to 10 kHz) are recorded on magnetic tapes on the routine basis (2 minute intervals at 50–52 minutes every hour). We make the aural monitoring of the recorded tapes and when we find aurally any VLF/ELF emissions, we display them as sonagrams. After the close inspection of all sonagrams of VLF/ELF emissions, we could find out 29 events which are definitely identified as VLF emissions triggered by whistlers. The requirement for a given event to be a whistler-triggered VLF emission, is that its initial portion is originated in the spectrum from a causative whistler. Most of the triggered emissions are rising tones (or hooks) except a few examples of hiss. We have found that triggered emission events take place mainly on different days, but some occur on the same day, but in different hours. So, the statistical characteristics in the following sections are considered to be meaningful even with such a small data set.

3. Characteristics of Whistler-triggered Emissions

We present the information concerning the occurrence of whistler-triggered VLF emission events, with emphasis upon local time, seasonal and K_p dependences, path latitude distribution and spectral property. The full line in Fig. 1(a) indicates the relationship between the occurrence number of whistler-triggered VLF emissions and UT(LT=UT+9h), and the broken line refers to the total occurrence number of whistlers recorded during the relevant ten years. The broken line indicates that the

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Fig. 1. (a) The diurnal variation of occurrence number of whistler-triggered VLF emissions (full line) and of the total occurrence of whistlers recorded (broken line). LT=UT+9h. (b) The seasonal variation of occurrence of whistler-triggered VLF emissions (full line) and the corresponding seasonal variation of total number of whistlers recorded (broken line). (c) The relationship of the occurrence of whistler-triggered VLF emissions with K_p index at the time of emission observation (full line), and the percentage occurrence of K_p values in each range (broken line).

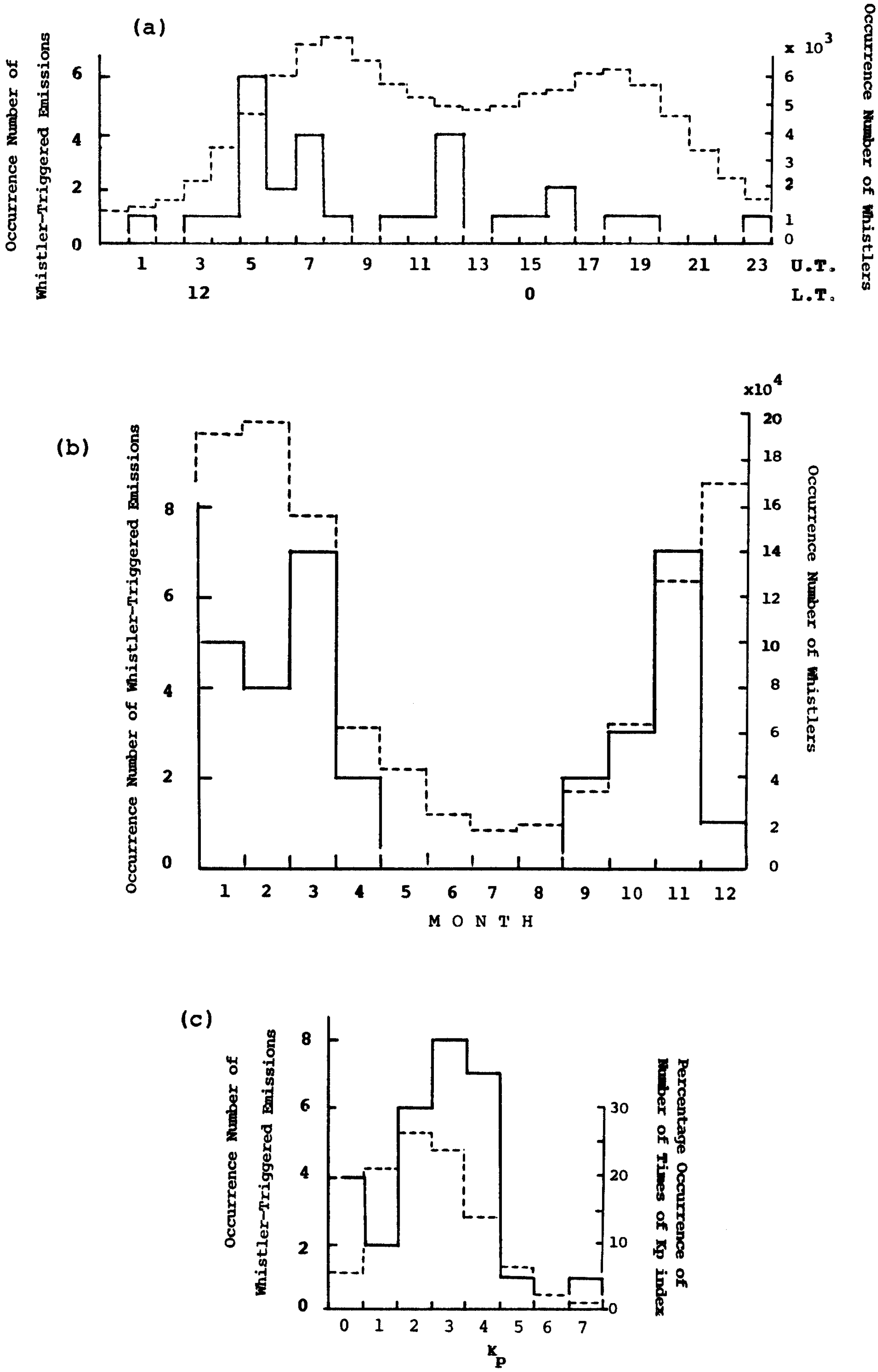

(a)
Occurrence Number of Whistler-Triggered Emissions
0
2
4
6
x 10^3
Occurrence Number of Whistlers
1 3 5 7 9 11 13 15 17 19 21 23 U.T.
12 0 L.T.
(b)
Occurrence Number of Whistler-Triggered Emissions
x10^4
0 2 4 6 8 10 12 14 16 18 20
Occurrence Number of Whistlers
1 2 3 4 5 6 7 8 9 10 11 12
MONTH
(c)
Occurrence Number of Whistler-Triggered Emissions
Percentage Occurrence of Number of Times of Kp index
0 10 20 30
0 1 2 3 4 5 6 7
K_p

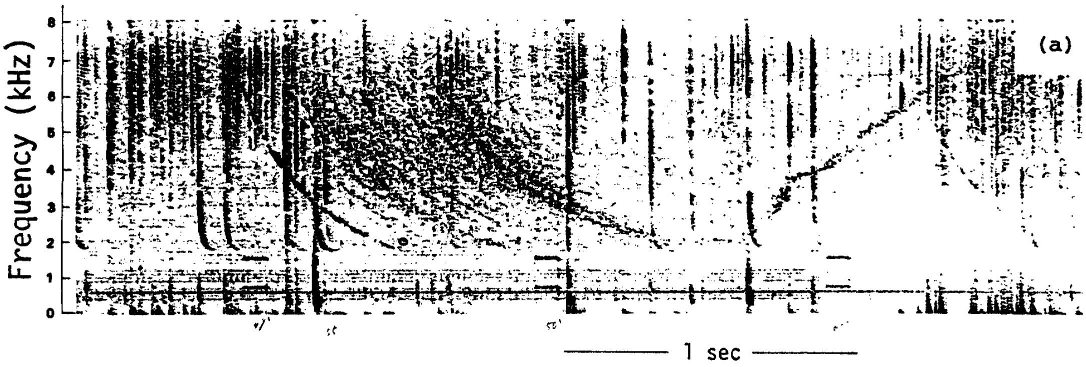
Fig. 1.

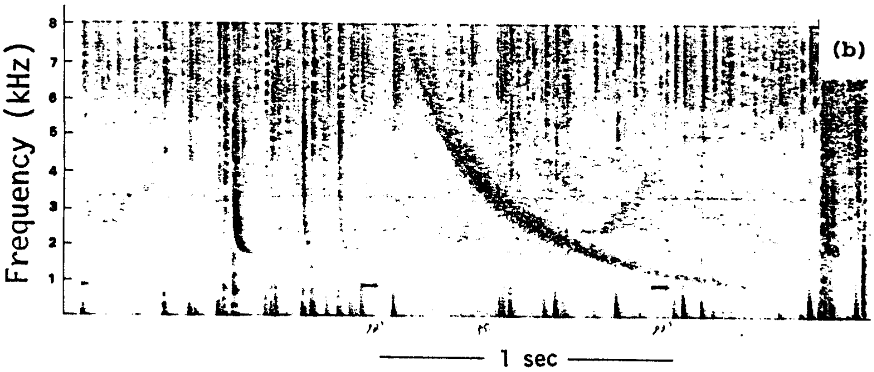
diurnal variation of total occurrence number of whistlers exhibit two maxima; a major broad one at LT=17h and a secondary broad one at LT=3h, and this pattern is consistent with the previous result at Wakkanai (very close to Moshiri) by KIMPARA (1961). However, when the latitude of the observing station becomes higher such as $L>2$, the whistler occurrence rate exhibits only a single peak between midnight and dawn (HELLIWELL, 1965). The ratio of the values given by the full and borken lines yields the occurrence probability of whistler-triggered VLF emissions, and there does not seem to be a clear tendency for whistler-triggered emissions to occur at a particular LT. So, the whistler-triggered emissions are found to occur over the whole LT though a small enhancement is seen at LT=14h.

Figure 1(b) illustrates the seasonal variation of whistler-triggered VLF emissions with a full line, while the broken line indicates the corresponding seasonal variation of the total whistlers recorded. The broken line indicates that the whistler occurrence rate at medium latitudes exhibits a maximum in winter (December, January, and February), and this is in agreement with the previous studies by KIMPARA (1961), HELLIWELL (1965) and HAYAKAWA *et al.* (1971). A comparison of the values by the full and broken lines implies that the occurrence probability of whistler-triggered VLF emissions shows a conspicuous enhancement in March, April, September, October and November, and the equinoctial occurrence maximum is likely to be an important characteristic of whistler-triggered VLF emissions.

Figure 1(c) illustrates the occurrence histogram of whistler-triggered VLF emission events versus K_p index at the time of emission observation with a full line, while a broken line indicates the percentage number of K_p values in each range during the ten-year span. By comparing the full and broken lines, it is found that the occurrence probability of whistler-triggered emissions is rather high at $K_p=0$ and there seems to exist a tendency of the occurrence probability to increase from $K_p=1$ at a value smaller than that at $K_p=0$, to higher values up to $K_p=4$. This increase in the range $K_p=1$ through 4 is likely to be significant because the occurrence numbers are rather great in this range. On the contrary, we cannot say definitely whether the occurrence probability still increases in the range of $K_p=5$ to 7 since an extremely small data number in this range prohibits significant statistics.

In Fig. 2 we present three examples of VLF emissions triggered by whistlers. In Fig. 2(a) we find a group of whistlers and a whistler with dispersion of 50 $s^{1/2}$ nearly at the end of the group appears to trigger a discrete VLF emission with a dynamic frequency variation. At the lowest end ($\sim$2.0 kHz) of the whistler spectrum, we notice a weak quasi-constant frequency component, followed by a sharp frequency increase and a subsequent small frequency increase. Then, Fig. 2(b) exhibits a slightly diffused whistler with dispersion of 55 $s^{1/2}$ and at a particular frequency ($\sim$2.4 kHz) within the whistler spectrum, we again find a constant frequency emission and a subsequent frequency increasing component. Fig. 2(c) indicates a discrete VLF emission triggered from the extreme end of the causative whistler spectrum. Its frequency increaes sharply for the first half and for the second half the frequency increases becomes slower. Figure 3 summarizes the spectral properties of whistler-triggered emissions including three examples in Fig. 2. The number of events in each panel is a little smaller than 29 because a few emissions are hiss as described in Section 2 and also it





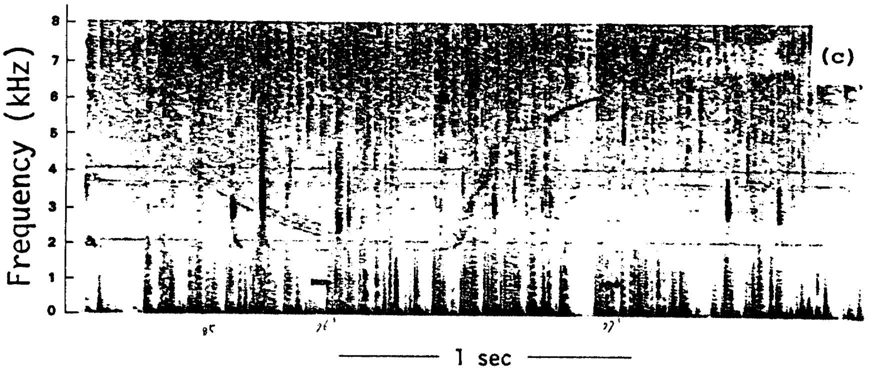


Fig. 2. Three examples of whistler-triggered VLF emissions. (a) 1978 November 6, 1050 UT. There are a group of whistlers and the last whistler is found to trigger a rising tone VLF emission from its extreme end of the spectrum. (b) 1979 December 31, 1850 UT. An emission is triggered from a whistler in a way such that it is initiated at a frequency of $\sim$*2.5 kHz within the whistler spectrum and it exhibits a sharp rising tone. (c) 1981 November 10, 1250 UT. A whistler is found to initiate a quasi-constant frequency emission component at the extreme end of the spectrum, and we notice a subsequent sharp frequency increase.*

was difficult to read some quantities for a few events. The second panel in Fig. 3 illustrates the local time variation of the frequency range occupied by triggered VLF emissions, and so the lowest tip of each bar indicates nearly the starting frequency of discrete VLF emissions. Then, the top panel in Fig. 3 illustrates that the local time dependence of the frequency drift of triggered emissions, df/dt(kHz/s) excluding the initial quasi-constant ($df/dt \sim 0$) parts. When the frequency variation of a discrete emission is approximated roughly by a straight line, or sometimes by two straight lines, its or their gradients are plotted. A study by YOSHIDA *et al.* (1983) on whistler-triggered VLF emissions has indicated that effective wave-particle interaction (leading to the generation of VLF emissions by whistlers) occurs in the off-equatorial region, and the starting frequency of a triggered emission gives the location of the interaction region. The top panel of Fig. 3 indicates that df/dt of a majority of triggered emissions takes very large values, generally of the order of 10–20 kHz/s or more, and even the smallest one is $\sim$2.0 kHz/s. These frequency drifts obtained for whistler-triggered emissions seem to be much larger than the normal values for chorus observed outside the plasmaspause by BURTIS and HELLIWELL (1976) and HAYAKAWA *et al.* (1984), but are nearly of the same order as for the discrete plasmaspheric emissions recently found by POULSEN and INAN (1988).

The bottom panel in Fig. 3 indicates the diurnal variation of the dispersion of the causative whistler in order to estimate the latitude range where the relevant whistler-triggered VLF emissions are generated. When the dispersion is indicated by a vertical line, it means that we had multi-path whistlers whose dispersion range is plotted. The curve connected by $\times$ is the diurnal variation of average dispersion of all whistlers observed at Moshiri during September through April over the relevant ten year span, and this is in good agreement with the previous finding by KIMPARA (1962) who indicated a slight maximum in dispersion at UT=12 h (LT=21 h). Hence, this curve is considered to correspond to the latitude of the observing station of Moshiri (L=1.6), and the comparison of the dispersion of the causative whistler with the average dispersion, can be used to deduce the path latitude (or L shell) of the generation region of whistler-triggered VLF emissions. We here comment that whistlers observed near Moshiri are likely to be attributable to ducted propagation (HAYAKAWA *et al.*, 1981) and whistlers at higher latitudes at $L>2$ are known to be ducted as well (HELLIWELL, 1965), although there is a report by THOMSON and DOWDEN (1977) that some ground whistlers are attributable to the prolongitudinal propagation at L=2–4. There has been no previous work on the wave normal directions of the triggered emissions, but it is very acceptable to presume that the associated emission has nearly the same wave normal angle as the causative whistler because both are considered to propagate in the same duct. Hence, the dispersion value can be used to deduce directly the L shell on which a VLF emission is triggered by a whistler. The bottom panel in Fig. 3 implies that the dispersions of the causative whistlers of triggered emissions are roughly grouped into two. One group consists of the dispersion located just around the average dispersion value, and the other is the group for which the dispersions are con-

Fig. 3. Summary of the spectral analyses of whistler-triggered VLF emissions. The top and middle panels illustrate the diurnal variations of the frequency gradient, df/dt of triggered VLF emissions (except the initial quasi-constant frequency components) (the arrows indicated upward at df/dt=30 kHz/s mean the df/dt being greater than 30 kHz/s) and the frequency range occupied by the VLF emission (the lowest frequency roughly corresponds to the starting frequency of VLF emission), respectively. The bottom panel indicates the distribution of the dispersion of the causative whistler. Each dot corresponds to each event and a bar indicates the dispersion range of multi-path whistler. The curve connected by × is the diurnal variation of average dispersion.

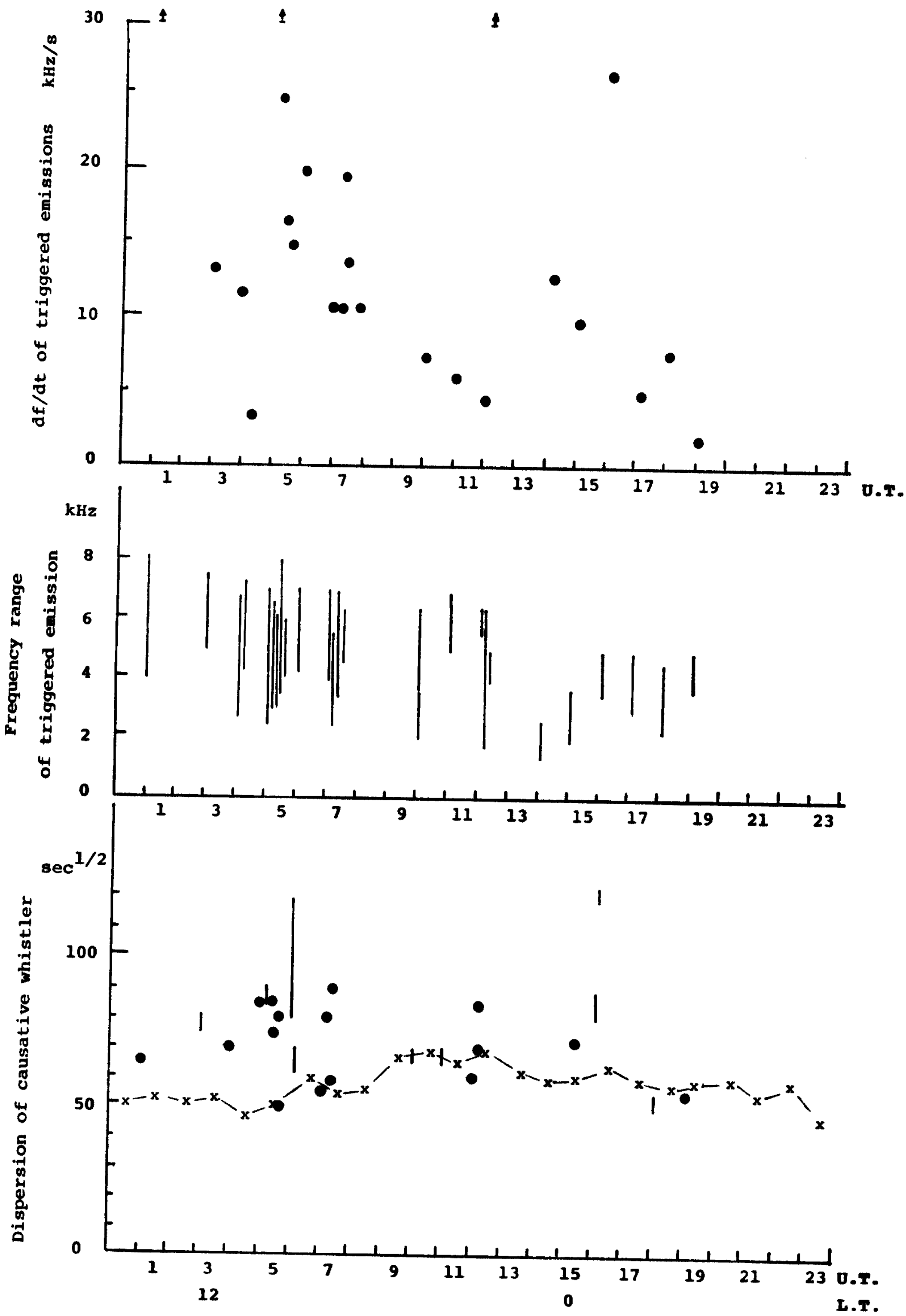

30
20
10
0
kHz/s
df/dt of triggered emissions
1 3 5 7 9 11 13 15 17 19 21 23 U.T.
kHz
8
6
4
2
0
Frequency range
of triggered emission
1 3 5 7 9 11 13 15 17 19 21 23
$sec^{1/2}$
100
50
0
Dispersion of causative whistler
1 3 5 7 9 11 13 15 17 19 21 23 U.T.
12
0
L.T.

Fig. 3.

siderably larger than the average one. First, we deal with the latter group. The dispersion for this group is always higher than the average value by a range between 20 and 40 $s^{1/2}$. By using ALLCOCK's (1960) empirical relationship $D=2.2(\Lambda-12)$ where D is dispersion ($s^{1/2}$) and Λ, the geomagnetic latitude (deg), the generation region of this group is likely to be at a latitude higher than the station latitude by 9° to 18°, and correspondingly L ranges from 2.14 to 3.19. These L values are known to fall in the region of the electron slot. Next, we discuss the first group. The generation region of whistler-triggered VLF emissions for this group is apparently around $L=1.6$ (and sometimes slightly below $L=1.6$) in the inner radiation belt.

4. Summary and Discussion

The statistical analyses of whistler-triggered VLF emissions during the ten-year span from 1976 to 1985, have yielded the following findings.

(1) A simple ratio of occurrence number of whistler-triggered emissions with the total whistler rate provides an occurrence probability of whistler-triggered emissions of the order of 10^{-4}.

(2) There does not seem to exist a clear tendency of whistler-triggered VLF emissions to occur at a particular LT, and equinoctial maximum in occurrence probability is recognized.

(3) The occurrence probability of whistler-triggered emissions seems to increase with increasing K_p index.

(4) The occurrence L shell of whistler-triggered emissions is grouped into two ranges; one is $L=2.1$ to 3.2 in the electron slot region and another just around $L=1.6$ in the inner radiation belt.

(5) The spectral feature of a whistler-triggered emission is such that the initial part of the emission starting from the whistler spectrum, is nearly at a constant frequency and the subsequent change is very dynamic with df/dt in a range mainly from 10 to 20 kHz/s.

The occurrence latitude of whistler-triggered emissions is estimated from the present study to be located in the electron slot region ($2.14<L<3.19$) as summarized in Item (4), which agrees with the corresponding L range of lightning-induced particle precipitations by HELLIWELL *et al.* (1973), CARPENTER and LABELLE (1982), LEYSER *et al.* (1984), VOSS *et al.* (1984), INAN *et al.* (1985), INAN and CARPENTER (1987) and CARPENTER and INAN (1987). This preferred L shell is likely to be consistent with the theoretical prediction by CHANG and INAN (1985). They have obtained the results that for higher energy (40–300 keV) electron precipitation due to the gyroresonance, there exists an inner magnetospheric region ($2<L<3$) where the level of whistler-induced precipitation can be expected to be relatively high. Hence, we would expect an effective wave-particle interaction in this L range, leading to the enhanced occurrence of whistler-triggered VLF emissions. Of course, none of the pitch angle scattering models as mentioned above, has considered the wave growth, and the conditions necessary for emissions are likely to be much more difficult to attain, which may be reflected as the low number of occurrences (Item (1)). The present study (Item (4)) has implied an additional occurrence region of whistler-triggered emissions around $L=1.6$ which corresponds to the location of the inner radiation belt. Our finding of the wave-side aspect of the gyroresonance is likely to be supported by a recent study by INAN *et al.* (1988) who have found that the region of whistler-induced precipitation extends even to the inner radiation belt ($L \lesssim 1.8$). The starting frequency of triggered VLF emissions is, on many occasions, in a range from 2.0 to 4.0 kHz as seen in the middle panel in Fig. 3, and so the gyroresonance electron energies for such frequencies of the causative whistlers are in the MeV range in the inner radiation belt.

Item (2) indicates that whistler-triggered VLF emissions occur over the whole LT when whistlers are recorded. The lack of clear tendency for whistler-triggered emissions is again in agreement with the corresponding diurnal variation of whistler-induced particle precipitation by CARPENTER and INAN (1987). This wide LT coverage of event activity suggests that the drift of electrons toward the dawn sector after their injection on the nightside are not a controlling factor, because HAYAKAWA (1989) has shown that the dawn sector is a preferred sector for substorm-associated VLF/ELF emissions.

As found in HAYAKAWA and OHTSU (1973), some whistlers observed at Moshiri are those which exited the ionosphere at a latitude much lower than the station latitude. Furthermore, our station, Moshiri, is not located in a place very suitable for the phenomena of whistler-triggered emissions at $2<L<3$ because of the attenuation during the propagation in the Earth-ionosphere waveguide. If we consider these two factors, the occurrence probability of triggering emissions by whistlers of the order of 10^{-4} (Item (1)) may increase to some extent. The joint influences on the activity of lightning sources and particle dynamics in the magnetosphere remain to be assessed.

The occurrence probability of whistler-triggered emissions increases with K_p index as given by Item (3) and this is in agreement with the corresponding behavior of lightning-induced precipitation by CARPENTER and LABELLE (1982) and LEYSER *et al.* (1984). This effect can be easily explained by an enhanced particle flux of resonance electrons during high geomagnetic activities.

The seasonal variation is noticeable as in Item (2). The austral summer drop in the activity of whistler-triggered emissions can be partly understood as due to reduced lightning source activity in the conjugate region, but the reduced activity in austral winter is difficult to understand. A factor which may be related to it, is a change in the energetic electron flux levels established at $L=2$–3 within the plasmasphere in the aftermath of severe magnetic storms. There is a semiannual variation in magnetic activity (*e.g.*, RUSSELL and MCPHERRON, 1973), and GREEN (1984) has found that this variation is dominated by the semiannual modulation, with equinoctial maxima, of the occurrence of severe storms. Another influential factor may be the semiannual variation of the electron density in the magnetosphere. A semiannual variation of the dispersion of whistlers is clearly noticed by HAYAKAWA *et al.* (1971) at Moshiri and by CORCUFF (1965) at Poitiers ($L=1.90$), in which the equinoctial maxima are apparent. An enhanced maximum in the electron density near the equator (even at slightly off-equatorial region where whistler-triggered emissions are generated (YOSHIDA *et al.*, 1983)) is expected in the equinoxes, and this means that the energy of resonant electrons for whistler-triggered emissions is lowered for more enhanced density (*e.g.*, BRICE,

1964) during equinoxes, which leads to an enhanced wave-particle interaction. Hence, the above two factors might be combined to produce the equinoctial maxima of the occurrence probability of whistler-triggered emissions, and this is consistent with the gyroresonance interaction between whistler waves and energetic electrons.

The detailed characteristics of spectral shapes of whistler-triggered emissions are summarized as Item (5). A further study of these properties is beyond the scope of this paper, and will be published elsewhere.

Acknowledgments

The author is grateful to his colleagues and members of VLF group of Nagoya University for their useful discussion. Thanks are also due to Mrs. H. YAMAGUCHI of VLF group for her careful data analyses. Finally, the continuous encouragement of Dr. A. KIMPARA, Professor Emeritus of Nagoya University is greatly appreciated.

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(Received May 31, 1990; Revised manuscript received October 11, 1990)